A PENETRATOR FOR THE JUPITER GANYMEDE ORBITER MISSION

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ABSTRACT

The Jupiter Ganymede Orbiter (JGO) forms the ESA contribution to the Europa Jupiter System Mission (EJSM), the other element of which is the Jupiter Europa Orbiter (JEO) provided by NASA. As part of the JGO studies, a Penetrator is being considered as a potential payload element for deployment on one or more of the Jovian moons.

This paper presents the mission concept that is being studied under ESA contract by a UK consortium involving Astrium (as prime contractor), Mullard Space Science Laboratory (MSSL) and QinetiQ. The key technical outcomes of the study, with respect to the system design, analysis of delivery trajectory and impact, impact modelling and planetary protection issues are presented here. In addition, the implications of this study are assessed with respect to other future applications for penetrators in the exploration of Solar System bodies.

1. BACKGROUND OF PENETRATORS FOR SOLAR SYSTEM EXPLORATION

Penetrators with their delivery systems are small spacecraft, carrying hardened subsystems and scientific instrumentation that impact planetary bodies at high speeds and bury themselves up to a few metres into the surface. They have the potential to provide both a significantly less costly alternative to soft landers (by virtue of their simplicity and reduced mass requirements) and the possibility of multiple Penetrators in a single mission at different locations to form a network of stations on the surface.

Penetrators/hard landers have been studied for a long time [1][2][3] and ground tests as well as developments through to flight have been undertaken. To date, three complete penetrator systems have been developed by international space organizations: NASA's Deep Space 2 probes [4], the Russian Mars'96 probes[5] and the Japanese Lunar-A spacecraft [6][7]. Of these, only Deep Space 2 made it to its final destination, impacting into the Martian surface in 1999, however no signal was ever received from them after deployment and their reasons for failure are unknown. The Mars'96 spacecraft failed to leave Earth orbit and Lunar-A was cancelled after an extended development period, but after a full ground test of the penetrator was demonstrated.

In May 2008 the UK penetrator consortium, demonstrated a first successful full scale trial of a penetrator (without delivery system) with impacts at over 300 ms^{-1} into a lunar regolith sand simulant. This demonstrated survival of the penetrator shell, power system, accelerometers, magnetometer, radiation detector, micro-seismometer sensors, mass spectrometer and drill components.

The current ESA-funded study, builds upon the experience of the UK Penetrator consortium by undertaking a system-level assessment of a complete Penetrator and Delivery System within the context of the JGO mission to icy moons of Jupiter as part of the Cosmic Vision 2015-2025 Programme. The objective of the study is to assess what the lowest mass solution of a Penetrator and Delivery system is, within the constraints of the JGO mission, and to show that it is feasible to accurately control and safely deliver a penetrator, with a meaningful scientific payload, into the surface of one or more of Jupiter's moons.

2. STUDY INPUTS AND CONSTRAINTS

As an input to the study, mass and volume constraints were provided at the level of 100kg and 2m x 2m x 1.5m, respectively. This was an absolute upper limit with the expectation that a minimum mass, minimum risk solution would be aimed for.

The other strong constraint for the study was to only consider solutions utilising technologies that would be at a Technology Readiness Level (TRL) of 5 by end 2012 in order to be compatible with the schedule of the JGO mission, planned for launch in 2020.

3. SCIENTIFIC CASE FOR PENETRATORS ON THE JOVIAN ICY MOONS

The deployment of Penetrators on the surface of the Jovian icy moons would add ‘ground truth’ to the orbital data acquired by the Orbiters of the EJSM mission as well as enable significant unique measurements to help answer key scientific questions about the origin, internal structure and habitability of these moons. The main science drivers of a landed element are to:

- Enable direct geophysical investigation including detection of any sub-surface ocean (surface, mantle and internal body structures, crustal and internal seismic activity).
- Enable direct subsurface chemical and mineralogical inventory.
- Enable direct astrobiological investigation.
- Enable comparison of surface element data with orbital studies and with other moons

4. OVERVIEW OF THE JUPITER GANYMEDE ORBITER MISSION

JGO is one of the candidates (referred to as ‘Laplace’) for the “L1” launch slot in the ESA Cosmic Vision plan, with a foreseen launch in 2020. All three currently studied L mission concepts (Laplace, IXO and LISA) are undergoing parallel studies with a down-selection at the end of 2010, when two mission concepts will be selected for definition studies, extending to the end of 2012. Eventually, the first L mission will be adopted for flight with an industrial implementation being planned for start in 2013.

According to the current baseline mission profile, JGO would be launched in 2020 on a Venus-Earth-Earth-Gravity-Assist trajectory to Jupiter. The inter-planetary transfer will take about 5.9 years. The initial Jovian orbit will be 13×245 R_J, followed by a total of four Ganymede and Callisto swing-by manoeuvres (GCGC). JGO will then be injected into a 2:3 resonant orbit around Callisto, which allows for 19 flybys at an altitude of 200 km, providing good surface coverage. Through another swing-by sequence (CGG), the orbiter will be injected into an elliptical orbit around Ganymede (200×6000 km), which will be circularized later in the mission, reaching a 200 km altitude orbit. The whole mission duration in the Jovian environment will last 3 years.

5. JGO-PENETRATOR MISSION ARCHITECTURE

For the JGO-Penetrator mission concept currently being studied by ESA, the Penetrator would make use of the JGO to ‘hitch a ride’ to the Jovian system. The JGO spacecraft cannot however deliver the Penetrator to the surface of a moon as required. A separate Penetrator Delivery System (PDS) is therefore needed to carry the Penetrator from JGO through to a controlled impact. *The PDS, being a mini-spacecraft in its own right, is an area that has not been studied previously in much detail and turns out to be the largest contributor to the total system mass and is therefore a major design driver (to minimise mass) for the Penetrator mission.*

The Penetrator Descent Module (PDM) incorporating both Penetrator and PDS, must separate from JGO at some allotted point in the mission. This separation could occur either early (on initial hyperbolic approach to the Jovian system), mid-mission (on hyperbolic approach to Ganymede from Jupiter), or late (from a stable orbit around Ganymede).

Of the latter case, two additional sub-cases are possible based on the JGO mission; release from either an elliptical or a (final) circular orbit. Both elliptical and circular release scenarios are shown in Fig. 1 and Fig. 2 respectively. In these cases, the PDM must perform manoeuvres to achieve the trajectory represented by the dotted line.

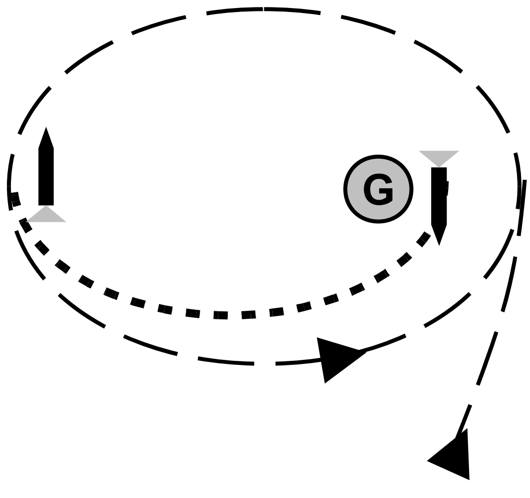

Figure 1: Elliptical Orbit Release Option

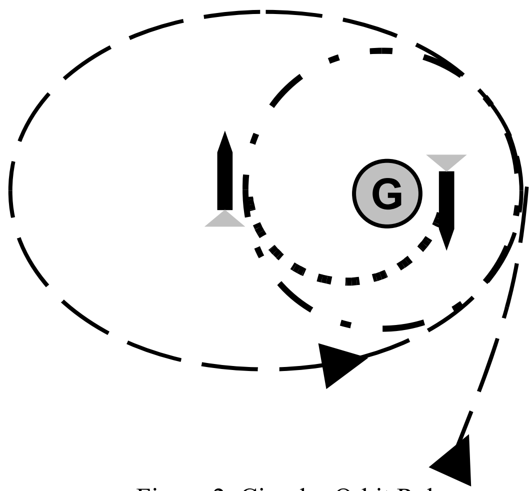

Figure 2: Circular Orbit Release

5.1 Deployment Trade-offs

Releasing the PDM from JGO during the hyperbolic approach to the Jovian system is attractive in terms of spacecraft propellant, and operational simplicity. By adopting this approach, JGO could reduce its propellant load due to the lower mass which would need to be 'slowed down' for the Jupiter capture manoeuvre (around 8kms^{-1}).

Unfortunately the PDM would have to take on board an additional propellant mass comparable to the mass saved by the spacecraft. In fact, it is expected that the large bi-propellant main engine on the spacecraft would be more efficient than the smaller thrusters needed by the PDS, therefore there would not be an overall mass saving by releasing the Penetrator early.

Furthermore, the complex Guidance, Navigation and Control (GNC) system onboard JGO will allow it to perform accurate gravity-assist manoeuvres, improving its efficiency further. It is considered unlikely that the PDS could achieve this level of control over such duration (in such a small package).

Release during the intermediate hyperbolic approach from Jupiter (around 3kms^{-1}) shares similar weightings, and while the gravity-assist benefit is increasingly expired as the mission progresses, the main engine remains the more efficient option.

All possible release scenarios and target Jovian moons were considered during the early trade-offs but ultimately the lowest delta-v (and hence propellant/system mass) option was to target Ganymede with a release of the Penetrator from the final circular orbit of JGO as shown in Table 1. Therefore, the Ganymede scenario was considered in more detail in the rest of the study.

Table 1: Release scenario Delta-Vs

Release Location towards Ganymede	**Impulsive DeltaV (m/s)**
Hyperbolic Ganymede Pre-capture	7698
Callisto Callisto Pseudo orbit tour	3192
Ganymede Elliptical orbit	2474
Ganymede Final Circular orbit	1955

Once JGO has been captured into a Ganymede orbit, the delta-V required to bring the PDM to a stop and freefall, is considerably lower than the values for the hyperbolic cases (around 2kms^{-1}).

In both the elliptical case, and the circular case, it is envisaged that the PDM would be released from JGO close to the apocentre of the transfer orbit (dotted line in Fig. 1 and Fig. 2.). A small retro firing (around 10-30 ms^{-1}) would be performed in order to lower the pericentre of this transfer orbit to around 32km.

At pericentre, the PDM would then perform a large de-orbit manoeuvre in the order of a 2kms^{-1} to bring the PDM to a standstill. The PDM would then enter a free-fall phase, reorienting itself during the descent, before impacting on the surface of Ganymede at around 300ms^{-1}.

The selection of Circular or Elliptical release is mainly driven by operational capability. In the elliptical case, only limited locations on the surface of Ganymede are accessible. This follows since the elliptical orbit is generally unstable, and relatively short lived. Ganymede rotates beneath this orbit by one complete revolution in around seven days. Variation in pericentre in both the longitude and latitude reflect the accessible areas. Communications coverage back to the spacecraft is challenging since the orbit has progressed around the moon relative to the Penetrator.

In the circular orbit case, the polar orbit remains stable for some months. This allows selection of an impact site at any longitude. There is also less discrimination between latitudes, since a release at any point in the orbit will be at 200km altitude regardless.

Communications availability in the circular case is more regular since JGO will be visible at least once every 3.5 Earth days (half a Ganymede day) given one ascending and one descending pass. The duration of these communications sessions will vary depending on the Penetrator antenna beamwidth, and the latitude.

Based on the trade-offs described above, a baseline scenario for the Penetrator mission to the Jovian system was established, targeting a single Penetrator, deployed from JGO, for a near-Polar landing site on Ganymede.

5.2 Baseline Scenario

JGO carries the PDM into the final Ganymede polar orbit of 200km. The velocity of JGO (and the additional mass of the PDM) is reduced considerably from the initial hyperbolic approach velocity. This reduction is achieved using a series of gravity assist manoeuvres, and orbit insertion firings using the JGO main engine. After a suitable period in orbit around Ganymede, allowing ranging to establish an accurate set of orbital parameters, and once Ganymede has rotated to the desired longitude; the PDM can be released.

The PDS carries the Penetrator to its target in around two hours. This allows several simplifications to be made to the system (compared to a conventional spacecraft), including passive thermal control, relaxed GNC integration error tolerance, and battery power.

Line-of-sight communications to JGO is maintained throughout the descent phase until the point of impact. The Penetrator is released from the PDS prior to impact to avoid damage or contamination from the propellant. To ensure stability it is spun-up to around 100 rpm prior to separation. The PDS performs a fly-away manoeuvre to ensure it impacts away from the Penetrator.

The Penetrator then performs around two weeks of science operations on the surface, driven by the science requirements for seismic data, and limited by the available battery power.

5.3 Science Payload and Scientific Objectives

The foci for the scientific investigations of Ganymede were identified as geophysics and geochemistry, with the following specific topics to be addressed:

1. Confirmation of existence and determination of ice depth to the subsurface ocean (High priority)
2. Determination of additional constraints to the internal structure (High priority)
3. Characterisation of the surface physical properties, and if possible their variation with depth (High priority)
4. Chemical composition of surface ice and regolith (Medium priority)
5. Astrobiology of surface and subsurface (Low priority)

For Ganymede, the science priority of geological investigations was rated higher than those for assessment of surface chemistry or astrobiological potential. Of course, if Europa were the target body, the scientific focus would include measurements of biological potential as a high priority together with the geophysics.

Based on the high priority topics, the consolidated model payload for the JGO Penetrator is therefore heavily weighted towards those instruments required for the geophysical investigation of the Ganymede surface and internal structure, as shown in . The scientific topics listed above that are specifically addressed by each instrument are also given in the table. As the investigation of astrobiological potential for Ganymede was of a low priority and due to the unknown effects on the shell integrity of apertures in the outer shell, astrobiological and chemical sensors which required direct sampling of surface material were excluded from the model payload.

Table 2: Proposed JGO-Penetrator payload

Instrument	Purpose	Science topic(s) addressed	Heritage
Micro-seismometer	Seismic activity	1, 2, 3	In development for Moonlite, Exomars
Accelerometer	Mechanical properties of the regolith	3	DS-2 and used in defense applications
Magnetometer	Magnetic field at the surface, presence of internal ocean	1, 2	New technology
Thermal Sensor	Temperature of the ice and regolith	3	Lunar - A
Microphone	Acoustic vibrations from cracking of surface ice	2, 3	Huygens
Descent Camera	Geological context of impact site and Public Relations	3	Beagle 2

6. PDM CONSOLIDATED DESIGN

An overview image of the concept PDM is shown in Fig. 3. The main sub-systems can be seen, comprising the propulsion, Reaction Control System (RCS) module, and structure, along with the Penetrator itself, and the spacecraft interface panel.

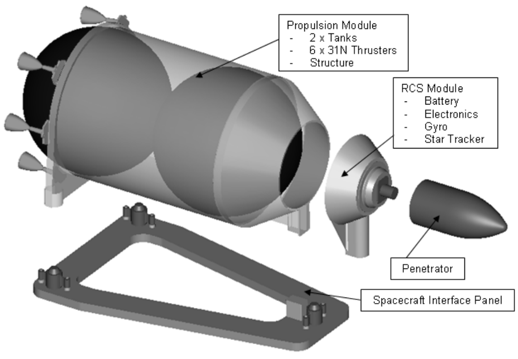

Figure 3: PDM Overview

6.1 Propulsion

The primary challenge for the propulsion system is to deliver sufficient delta-V with the minimum mass. To provide the total delta-V of around 2055ms^{-1} requires a propellant loading which almost matches the dry mass of the PDM (depending on the technology used). In this case a blow-down bi-propellant system is found to be optimal. This selection makes certain assumptions however, and this does not hold true for every Penetrator mission – as the delta-V requirement and system mass vary, so other technologies become more or less favourable.

Benefits of the blow-down system in this case include a high I_{sp} (over 300s), limited dry mass (no regulators or pressurant tank) and the ability to modulate the output thrust.

Alternative approaches may adopt a solid rocket motor for the de-orbit, combined with a cold-gas, or mono-propellant system to provide control during other phases. These approaches were found to be less mass efficient for this baseline mission scenario.

The propulsion system is the only system available to assert control during the descent and as such must perform several functions as follows: attitude control, pericentre lowering manoeuvre, de-orbit, re-orientation, and spin-up/down.

To provide all of these control capabilities, four of the thrusters are canted away from the Z-axis (the long axis). This enables a torque element to be imparted through the use of various combinations of thrusters, allowing 3-axis control, but with minimal geometric losses during the main de-orbit burn, which otherwise requires the thrusters to be aligned to the z-axis. Fig. 3 shows the PDM, with the propulsion system, represented by two large spherical tanks, and six 31N thrusters.

6.2 Thermal

Thermal control of the Penetrator after impact, as well as the PDM prior to and following release have their own challenges. Multi-layer insulation (MLI) on the outer surface of the Penetrator was avoided to mitigate the risk of obscuring communications following impact. Consequently, exposing the Penetrator shell to the solar flux at close range (~1AU) causes it to heat up rapidly.

This imposes an operational constraint on the spacecraft to avoid long periods of Sun-pointing during the early phases following launch.

In the cold case, when the PDM is pointing away from the Sun however, the Penetrator is inclined to cool. This is limited by adopting a polished metal surface on the Penetrator – this is also the natural finish.

Heat-loss from the PDM is important in the later phases, as power becomes less plentiful further from the Sun. This is managed using conventional spacecraft design methodology.

The main thermal challenge is that the Penetrator is in intimate contact with the target material, which is largely water ice at temperatures reaching as low as 70K. The associated heat-flow is large when compared to radiative coupling in conventional spacecraft.

Adopting highly insulative materials such as aerogel would still be inadequate to provide the required isolation of the sensitive sub-systems such as the battery, from the outside environment. Shock resilience is also problematic for such materials.

The proposed thermal solution for the Penetrator makes use of a vacuum flask concept, whereby the inner bay structure is held away from the outer wall, meaning that the main heat flow mechanism becomes radiative, as depicted in Fig. 4. The gold-plated vacuum chamber transfers less that 0.5W at the worst case operating temperature differential. Other conductive losses remain due to structure and electrical interfaces, but these must be strictly managed.

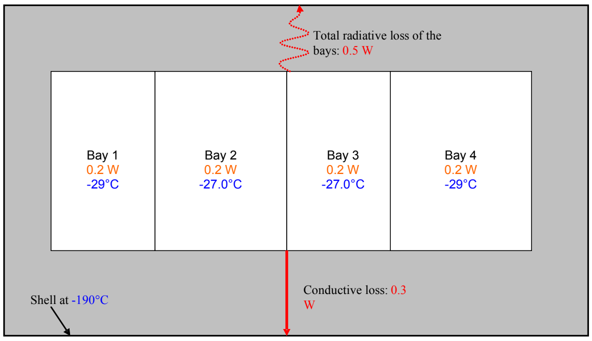

Figure 4: Penetrator Thermal Model

Adopting an RHU to provide heating has been considered, but this adds additional risk due to the unknown parameters of the target material, and the extent of coupling between the surface and the Penetrator. This makes the RHU difficult to size, leading to either an overheated or frozen Penetrator. Additional control mechanisms are also to be avoided due to the shock environment.

6.3 Guidance, Navigation and Control

The GNC system of the PDM is provided its orbital parameters by the JGO spacecraft just prior to release. The PDM is then released from JGO and tumbles slowly away, initially implementing no control.

The PDM drifts away for about 1000s to a safe distance away from JGO. The GNC system now performs a lost-in-space attitude acquisition, and re-orientates the PDM ready for the PLM.

This requires either a star-tracker (STR), inertial measurement unit (IMU), or other combination of sensors. Given the prior attitude knowledge from the spacecraft, the IMU is able to propagate the heading at this point. This is redundant however, and a micro-star camera is used for this purpose. The STR is essential later in the descent phase due to IMU integration deterioration (a high-accuracy device is too massive to consider adopting on the PDS).

The PLM is performed, and attitude is maintained using the STR throughout the transfer orbit.

The PDS is now aligned for the de-orbit burn – the STR remains able to calibrate the IMU. The burn is performed, propagating the IMU data throughout. At the end of the manoeuvre, the STR re-acquires the attitude (calibrating the IMU), before re-orientating the PDM, and spinning-up to 100rpm. The IMU remains operational during the short free-fall descent (while the STR is inactive).

An alternative passive approach has been considered, but the risks to the spacecraft and the lack of accuracy in terms of the impact angle are unacceptable once a comprehensive error budget has been assembled.

6.4 Penetrator design

The Penetrator shell design was consolidated around stainless steel because of the extensive heritage of impact survival within the defence sector, additionally supported by specific impact modelling into the anticipated Ganymede ice impact materials. The inner structure is compartmentalised in order to aid AIV. Each compartment (bay) is mounted (stacked) within the outer shell body (150mm outer diameter and 400mm long), being held away from the outer shell structure by a series of precisely placed snubbers. The snubbers provide both a low thermal conductance path and excellent shock absorbing properties (deforming at the point of impact and returning to normal length fractions of a second later). The snubbers also provide a means of preventing the build up of charge within the Penetrator inner systems, which would otherwise lead to a possible electro-static discharge event and corresponding instrument failure. Fig. 5 shows an illustration of the final JGO Penetrator design.

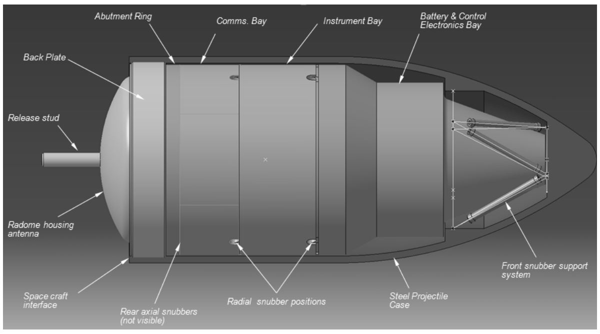

Figure 5: JGO Penetrator illustrating outer shell and internal instrument bays

Excellent radiation protection is provided by the stainless steel body of Penetrator (5mm outer shell wall plus 4mm inner bay wall), enabling access to a more comprehensive range of components/equipments than might otherwise be expected.

Each compartment bay holds a set of Penetrator equipment (batteries, scientific instruments and communications) with some overlap in order to improve packaging efficiency. Compartments have been configured in order to control the Penetrator CoG to minimise deviation of the Penetrator from its nominal impact trajectory during impact.

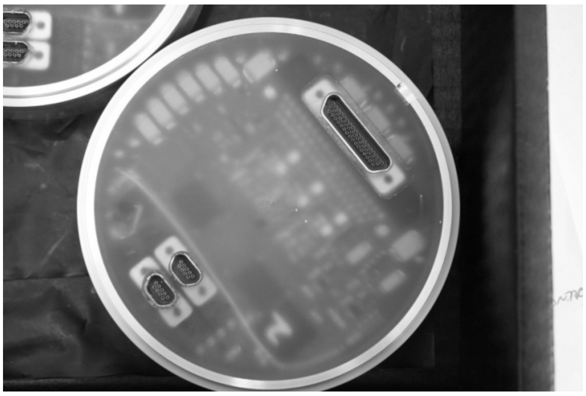

Figure 6: Penetrator compartment. Micro-D Metal connectors can be seen extending through packing material (electronics components are visible)

Compartment bay interconnections (electrical) are made via Micro-D Metal connectors, providing an efficient stacked solution (concept successfully verified during the Pendine trials 2008) and preventing the need for electrical harnesses (copper mass and thermal shunting issues).

The Penetrator has been designed to include all the scientific payload instruments defined in Table 2, and will operate for a period of two Ganymede days (approximately 2 weeks). Instrument operation has been carefully considered in order to reduce power demands over this period. Electrical power is provided by Li-$SOCl_2$ primary batteries, mounted in the nose section of Penetrator. Battery ageing/self-discharge (during a 9 year cruise phase) has been accounted for in the design margin.

On-board management of the Penetrator is provided by a bespoke data processing unit, comprising a low power consumption SPARC microprocessor (90MIPS), FRAM memory and operating in a wishbone-type architecture, providing superior flexibility in terms of power and re-configuration. The DPU regulates the internal thermal environment of the Penetrator through switching of electrical heaters, sequences instrument activity, collects and processes instrument data (including data compression), manages on-board data during orbiter out of contact periods (<3.5 days), and sends data to the Penetrator communications system.

6.5 Communications

The Penetrator communications system is mounted at the rear of Penetrator and adopts a UHF transceiver similar to that used on Beagle-2, partly due to heritage, but also to limit the attenuation though the target material (which rolls-off with frequency). This in turn limits the possible data rate, however data rates up to 256kbp/s can be achieved using the Proximity-1 protocol, which has been used extensively on recent Mars missions.

The patch antenna is mounted on the outward facing side of the rear plug. RF energy between the transmitter and antennae is coupled across the Penetrator vacuum gap in order to preserve the thermal environment (thermal conduction issues associated with copper harness violate demanding thermal management requirements of the Penetrator). RF energy has been sized to account for as much as 3 meters of water/ice material backfill behind the Penetrator following impact.

Communications challenges fall under two main areas; firstly the ability to maintain communications during the entire descent sequence until impact, and secondly the scope for uplink of data following impact.

During the descent, the PDM lags behind the orbiter after the PLM is performed. If this is not corrected for in the trajectory then JGO will pass below the horizon before the Penetrator reaches impact. It is taken as an important requirement to ensure communications at least up until impact; therefore this adds a constraint to the descent trajectory. Beyond this geometrical issue, if a line of sight is maintained, then adequate communications power and bandwidth is available for the limited flags which need to be passed during descent.

Following impact, several challenges are prevalent. The geometry of visibility to the orbiter is constrained by the altitude of the JGO orbit (200km), and the Penetrator antenna beamwidth (assumed to be $\pm 30^{\circ}$). Initial analysis of this problem is shown in Fig. 7 which shows the total communications time (over the whole two week surface phase) against target latitude. Since JGO is in a polar orbit, high-latitude sites offer more opportunities for communication with the Penetrator.

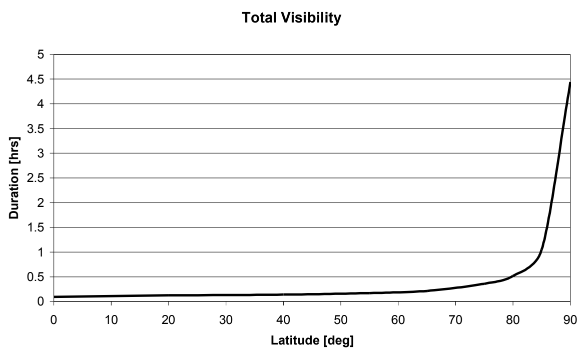

Figure 7: Communications Coverage with Latitude

The Penetrator will generate up to 200 Mbits of data over the course of its descent phase and 2 weeks of surface operations. This data will be transmitted to the orbiter over the course of a number of discrete contact periods, each separated by 3.5 days. Data will be prioritised prior to transmission as far as possible in order to control risk.

Based on the coverage graph, and the UHF data rate; a target latitude of greater than 75° is selected. Lower latitudes are unable to support an acceptable data volume based on the given instrument compliment, transmitter power, anticipated surface attenuation, and antenna gain. This will vary for other missions, but with similar issues.

It should be noted that higher latitudes become less attractive due to falling surface temperatures, despite the possible improvement in communications.

6.6 Mass budgets

The final JGO-Penetrator mass budgets for the PDM are as presented in Table 3.

Table 3: Mass budgets for PDM

Item	Mass (kg)
Payload	< 1
Penetrator	15.4
PDS (dry)	27.2
PDM (dry)	42.6
PDM (wet)	85.0

As Table 3 shows, the Penetrator itself only forms a small part (about 20%) of the total PDM system mass. The propellant mass itself for the Ganymede application accounts for half of the total mass. Clearly, such a mission scenario, with the large Vs involved (and hence propellant requirements), greatly limits the possibility of deploying very low mass Penetrator systems.

7. DESCENT AND IMPACT TRAJECTORY

The trajectory is primarily optimised for minimum propellant mass whilst maintaining visibility to JGO. The ideal impulsive case is not practical due to the relatively low thrust to mass ratio (180N / 85kg).

To ensure visibility throughout the final descent, the PDM must catch up to the spacecraft which has moved ahead due to the pericentre lowering manoeuvre which slowed the PDM by around $30ms^{-1}$.

By selecting a lower pericentre, the PDM moves faster through its orbit, catching up, and overtaking JGO. A safe minimum altitude is imposed, limiting this to 8km. The de-orbit burn starts shortly after pericentre, with an off-track thrust component to ensure that the PDM ends the burn at 32km altitude, ready for the free-fall acceleration to $300ms^{-1}$. This final impact velocity was chosen as it represents both a survivable impact speed as well as ensuring sufficient (of the order of a few metres depending on the surface material hardness), penetration into the surface to provide a predictable final configuration of the Penetrator. This is important to allow the desired communications geometry between Penetrator and JGO to be achieved.

Various combinations of thrusts and angles can be explored for a given mass. The 180N case baselined here proves to be optimal for this scenario, but is likely to be adapted for other scenarios including different targets or mass.

Fig. 8 outlines the descent trajectory, starting at the PLM on the left, and ending at impact. Both manoeuvres are identified by the thick dotted lines. The lower line represents PDM altitude, starting at 200km, and falling to 8km before recovery to 32km. The upper line represents PDM speed, and starting at around 2kms-1, initially increases towards pericentre, before rapidly reducing during the main burn, and finally accelerating again during the free-fall.

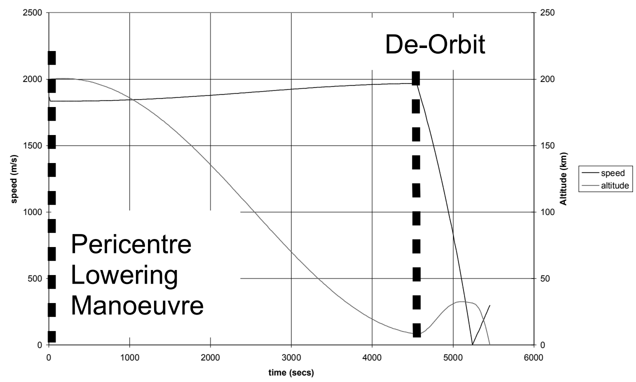

Figure 8: Descent Trajectory

An overview of the descent timing is provided in Table 4.

Table 4: Descent Timing

Event	Start Time [s]	Duration [s]	Altitude [km]
Release & Drift	**0.0**	**1000**	**200**
Attitude Capture	**1000**	**200**	**200**
Pericentre reduction burn	**1200**	**17**	**200**
Transfer	**1217**	**4532**	**8**
De-orbit burn	**5749**	**691**	**32**
Re-orientation	**6440**	**20**	**31**
3-axis free-fall descent	**6460**	**60**	**27**
Spin-up & Separation	**6520**	**80**	**14**
PDS fly-away manoeuvre	**6600**	**50**	**0**
Penetrator freefall	**6600**	**50**	**0**
Impact	**6650**	**0**	**0**

8. IMPACT MODELLING

The impact modelling was performed by QinetiQ, UK, utilising the DYNA3D Lagrangian hydrocode and was intended to assess the proposed design for impact survivability into water ice at -10°C. Little data exists in the literature of the structural properties of ice at the temperatures expected at Ganymede (-170°C), so a first iteration of the modelling was done using data at the lowest temperature available. The general approach in designing the Penetrator employed a combination of hydrocode modelling and finite element strength of design analysis as well as the general experience and heritage of QinetiQ built on 40 years work for the UK Ministry of Defence on penetrators for ballistic applications.

An Equation of State using a physics-based approach due to Porter-Gould [8] and constitutive model was constructed for ice assuming a compressive strength of 10MPa and validated against data as shown in Fig. 9. Validated material models were used for the Penetrator shell material [9].

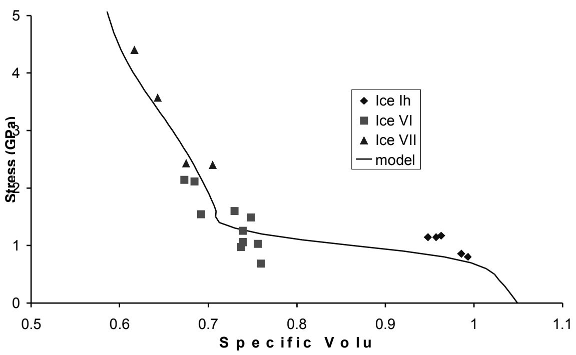

Figure 9: Prediction of Porter-Gould equation-of-state with experiment for water ice

Scoping simulations were performed to identify the peak longitudinal and lateral loads on the Penetrator. These were input into the finite element (FE) analysis to produce a design within the specified mass and volume constraints. This analysis suggested that an EN24 steel Penetrator should achieve this objective. The analysis also suggested that a shorter L/D Penetrator would be less prone to deformation than a longer L/D Penetrator. The payload for this work was assumed to be a constant density polymer using a validated high strain rate material model. The shorter L/D Penetrator also allows some of the payload to be put in the nose. The final Penetrator shell mass was about 6kg, with a length of about 350mm and max diameter of 150mm, with an ogive nose.

Simulations were then performed to assess the survivability of the design for the specified impact condition. The results demonstrated that the Penetrator would survive the impact with < 1mm of permanent deformation of the Penetrator shell along its length. The simulations also demonstrated that the Penetrator would survive impact into a much higher compressive strength ice. However, the Penetrator was predicted to move off-axis as shown in Fig. 10.

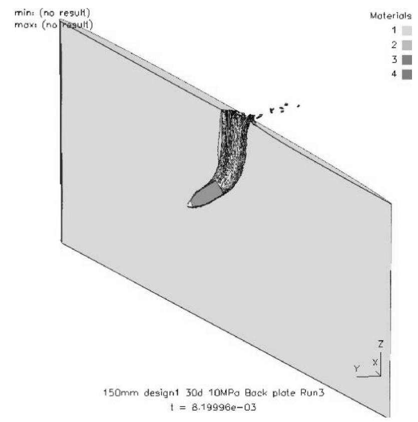

Figure 10: Predicted Penetrator path in ice

This is largely due to the asymmetric loading of the Penetrator but it can be corrected by moving the CoG further forward, however this requires further investigation. The average deceleration was of the order 6000Gs, although the peak transient loads were much higher but of short duration. Further investigation is required to quantify the effect of these transient loads on the payload instruments and sub-systems, which can be achieved by a programme of integrated modelling and small-scale experiments. Experience in the defence field suggests that these transients do not necessarily damage the components but is dependent on the frequency response of the component, which can be modified by suitable mounting techniques and use of mitigant materials.

9. PLANETARY PROTECTION

An important aspect of any mission that will come into contact with planetary surfaces with astrobiological potential (Mars, Jovian moons, etc) is Planetary Protection (PP). Even for orbiter missions, PP has to be considered carefully due to the risk of inadvertent contact/crash onto the target body during interplanetary cruise or science operations phases.

The PP aspects of a Penetrator mission to the Jovian system have so far been considered in this study only for Ganymede as a target body. However, the COSPAR categorization for a lander on Ganymede is currently only a Category II+ (*denoting a body that is of interest to chemical evolution and the origin of life, but whose potential to support living organisms is undecided*[10]). Therefore, no significant mitigation measures (e.g. Dry Heat Microbial Reduction) are required at the hardware level for the Penetrator (or for JGO for that matter, which will end its life in a controlled impact onto the surface of Ganymede). Furthermore, the relatively shallow penetration depth of the Penetrator (of the order of a few metres) compared to the much greater anticipated depth of any subsurface ocean effectively eliminates any risk of transferring biomaterial into any possible life-sustaining region of the moon. Therefore, the impact of PP constraints on manufacture, integration and test of the Penetrator will be minimal, principally comprising a PP reporting process as outlined in the COSPAR PP Policy Document [11].

Alternative targets, in particular Europa, would necessarily require a re-evaluation of the PP categorisation for the Penetrator mission and associated PP requirements.

10. RISKS

The main risks associated with the Penetrator element of the mission can be broken down into several groups as outlined below.

10.1 Target Material and topography unknowns

The level of characterisation for the surface materials on Ganymede is limited due to the limited exploration of the Jovian system performed thus far. Despite analysis of the available data, it is inevitable that the resolution of data will remain inadequate due to the scale of the Penetrator and the impact area (the highest resolution data available of the Ganymede surface is >50m/pixel). The nature of the Penetrator means that it is intimately dependent on the surface parameters which affect impact survivability, penetration depth, thermal losses and RF attenuation.

Important parameters which are difficult to define are:

- Surface Hardness
- RF attenuation (dielectric permeability)
- Local features – rocks, extreme slopes, etc
- Temperature and heat flow

Specifically, one of the major risks to the success of the Penetrator mission is penetrating too deep into the surface (due to the material being much softer than anticipated) and thus being unable to communicate back to the Orbiter due to the attenuation of the UHF signal.

Another significant risk is that the local slope at the point of impact is too steep to permit controlled penetration into the surface, but rather causes a ricochet of the shell along the surface, or high impact loads transverse to the long axis of the Penetrator (which is the strengthened axis).

It is conceivable that the design of the Penetrator itself, and to some extent the mission profile may to some extent allow increasing the robustness of the impact conditions to uncertain surface parameters, however some of these risks will still not be able to be eliminated or reduced to a very low level.

10.2 Development

New developments of hardware will be needed to support the unique requirements of the Penetrator mission. This is mainly due to the high-shock loading which must be survived, or the challenging thermal needs of the impacted system. The main sub-systems requiring development are expected to be:

- Penetrator Battery
- Thermal Concept
- Interfaces and Interlocks
- All electronic sub-systems for shock

In general, the requirement to achieve TRL 5 at 2012 has been adopted. This mitigates most development risks, but also constrains the possible choices of technology significantly. In turn, this is a main design driver for the Penetrator system, e.g. in terms of external access to the ice and surface material, and subsystem miniaturisation.

10.3 Conventional Risks

Besides the risks associated especially with the Penetrator development and operations, there remain more conventional spacecraft type risks including:

- Component & Sub-system failures

- Failure management
- Redundancy philosophy
- Delivery error management

The redundancy philosophy is particularly sensitive since the propellant loading is heavily dependent on dry-mass, leading to an inclination away from redundancy for the heavier items such as thrusters and the larger GNC components.

11. SUMMARY AND CONCLUSIONS

A system assessment study of the use of a Penetrator for in-situ science as part of the JGO mission to Ganymede has been undertaken. A low-mass, technically feasible solution was sought, in order to be compatible with accommodation on the JGO spacecraft, which is currently being studied for a mission to the Jovian system in 2020 as part of the Cosmic Vision programme. However, the large delta-Vs involved in reducing landing speeds to survivable levels (even for a hardened Penetrator system), results in a design with a total system mass of Penetrator and delivery system approaching 100kg, for a 15kg Penetrator on the surface with a less than 1kg payload complement. This is particularly the case for landing on airless bodies such as the Jovian moons due to the unavailability of atmospheric braking capabilities, which could otherwise reduce the mass of the PDS by a significant amount.

The other important issue highlighted in the study is the sensitivity of the design of a Penetrator mission to knowledge of the target material and topography. The relatively unknown surface properties of Ganymede (e.g. in terms of material hardness, thermal conductivity and RF properties) results in significant risks to the Penetrator mission that cannot be easily mitigated without considerable growth in the design complexity, mass and cost. In contrast, the somewhat better characterised properties of the surface of Mars offer a less-demanding (softer material, warmer environment) and less risky target. In this sense, it appears that in general, if very low-mass and low-risk Penetrator systems are desired, they may be best employed on targets where considerable knowledge of the surface properties already exists.

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